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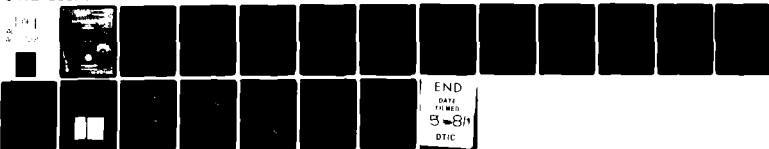
DRAW ENHANCEMENT OF MICROBIAL SLIME FILMS ON ROTATING DISCS.(U)

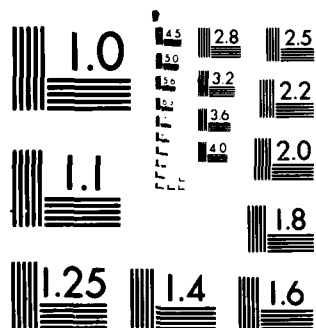
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*cont.* 9.5 to 33 Kn (17 to 61 Km/hr) showed that (a) microbial slime films can be grown which withstand testing at these velocities and (b) drag increments in excess of 10% are often observed. Therefore, because they are not eliminated by current antifoulants, microbial fouling films and their effects on ship performance warrant serious consideration.



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## DRAG ENHANCEMENT OF MICROBIAL SLIME FILMS ON ROTATING DISCS

### INTRODUCTION

The development of modern antifouling measures has made the possibility of control of the familiar macroscopic fouling organisms credible. As this goal is achieved, the remaining causes of drag on ship hulls and deterioration of propeller efficiency become important limiting factors in the performance capability of naval vessels.

In recent years it has become apparent that the term "antifouling" is too general, so that it has become misleading. This is because the toxic properties of coatings which successfully prevent development of the large and easily visible organisms, such as barnacles, bryozoa, and tubeworms do not prevent attachment and growth of micro-organisms, which may develop into large colonies. These colonies are easily detectable, and their nature is reflected in their common description: i.e., "slime". While it has been generally appreciated that the prominent rigid protuberances resulting from the calcareous barnacles, bryozoan colonies, and tubeworms would have an impact upon surface roughness, and thus hydrodynamic drag, the effect of the less apparent and soft microbial slime film fouling on drag and propeller efficiency has not received as much attention. Indeed, there was not much reason to be concerned with slime films until the modern antifoulants became available, although reports of possible effects of slimes were available (1). It is now known, however, that copper and organotin-containing coatings may actually stimulate slime formation (2), (3), and reports of the effect of non-rigid materials on frictional coefficients of fluid flow have indicated the possibility of quite significant drag increments (4). The effects of slime upon towing tank measurements, analagous to an increase in roughness (5), and upon flow through tubes, reducing flow at a given pressure gradient as sliming increases, have also been reported (6).

The significance of microbial films for operational vessels, however, was not understood for two reasons. Firstly, the speeds attained by present and postulated ships might be expected to prevent attachment and growth of organisms, or to cause erosion of slime films formed under more moderate flow conditions. Secondly, the nature of the interaction between the microbial film and the rapid flow has not been analyzed sufficiently to allow prediction of drag increments with any degree of confidence. Neither the range of viscoelastic properties which slimes can exhibit, nor of the values of those

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properties which are of hydrodynamic significance, is well known although some experiments with compliant plastics cited above (4) have been partially interpreted in terms of their elastic properties. In order to attain an assessment of possible slime film significance upon ship operations, microbial slime films of several types were allowed to form upon test specimens and subjected to hydrodynamic drag testing over a range of conditions including flows as severe as expected on fast vessels. Because particulates present in natural waters might become incorporated into microbial slimes grown in them, leading to misleading values of drag enhancement, we have emphasized laboratory-grown microbial slimes in this work, and compared them with some slimes from the Severn Estuary.

The results of this study indicate that slime films can be sufficiently tenacious to significantly enhance drag at operational speeds. Good understanding of the interaction of slimed surfaces with flowing liquid, however, will require further study.

#### Hydrodynamic Testing

The effect of microbial films upon hydrodynamic friction was assessed by measuring the torque required to rotate a 9 inch (22.9 cm) diameter disc at constant angular velocity while immersed in a cylindrical tank. The tank was 32.5 cm in diameter, and 25.4 cm in height. The discs were 1/8" (3.2 mm) thick. The range of angular velocities was from zero to 1400 RPM, corresponding to the range of peripheral velocities of zero to 32.6 Km. Early experiments were performed with a friction disc machine located at the Carderock facility of the David Taylor Naval Ship Research and Development Center (NSRDC). Those experiments were described previously (7). The later work described in this report was done using a similar apparatus (shown in Fig. 1) at the Annapolis laboratory of the NSRDC. The procedure for carrying out a test of a slimed disc was as follows: After a preliminary warmup of the drive train, consisting of the electric motor, drive shaft, bearings, electronic speed control and torque sensing units, the torques generated with the drive shaft spinning in air at the speeds to be used for testing but without a disc attached were recorded to determine bearing friction corrections. The slimed test disc was then attached to the shaft, and immersed in the cylindrical tank filled with fluid appropriate for the particular slime film under test. The torque generated at each of the rotational speeds was observed and recorded after a stable value was reached, starting at ~400 RPM and progressing to 1400 RPM. The rotational speed was then reduced stepwise and a torque measurement was made at each of the same rotational speeds. The disc was then removed from the shaft and cleaned under running tap water. Cleaning was accomplished by brushing with a plastic bristle brush in the case of metal discs, or in the case of plastic discs wiping with a rubber blade and polyvinyl chloride gloves until (a) no growth was visible (b) the surface was no longer "slippery" and (c) water drained off to leave a dry surface,

rather than a thin water layer. The clean discs were then attached to the shaft and the torques measured at the same speeds as when the slimed discs were tested. Finally, the torque generated by the shaft spinning in air was again measured. After correction for bearing friction, the torques generated were converted to moment coefficients (8) according to the equation:

$$C_m = Q \left[ \frac{\rho \omega^5 R^5}{2} \right]^{-1} \quad \text{where } C_m = \text{moment coefficient, } Q^* = \text{observed torque, } \rho = \text{fluid density, } \omega = \text{angular velocity, and } R = \text{radius of the disc.}$$

In the following discussions,  $C_{m_s}$  and  $C_{m_c}$  refer to moment coefficients for slimed and cleaned discs, respectively. Densities and viscosities of the medium were corrected for temperature.

Rotational Reynolds ( $R_{Rot}$ ) numbers were calculated from the relation:

$$(R_{Rot}) = \frac{R^2 \omega}{\nu} \quad \text{where } \nu \text{ is the kinematic viscosity of the fluid.}$$

Figs. 3, and 5 to 11, present the results of the drag tests in graphical form, where  $C_m$  is plotted against  $\log R_R$ . At a given value of  $R_R$ , the % increase in drag is given by the ratio

$$100(C_m - C_o) / C_o$$

Previous experience with rotating disc apparatus has indicated that torque at low rotational speeds is sometimes unreliable because (a) bearing friction is a significant portion of the observed torque and is not truly constant during an experiment, and (b) the turbulent rotational regime in the fluid is not always well established. For this reason, drag at values of  $\log R$  below 6.0 may be expected to be somewhat erratic (Laster, private communication). Because we were not certain whether the slime films would be retained by the discs under test conditions, data at low speeds were recorded, and are shown in figures 3-11. The lack of reproducibility at the low speed range is evident in some of the data: (Figs. 5, 6, 8 & 11). However, the differences between slimed and cleaned discs are clear when both slimed and cleaned discs are subjected to increasing speeds, and also when both are subjected to decreasing speeds.

### Slime Film Thickness

Microbial slime film thickness was measured with the light section microscope. This instrument and its use have been described previously (9). The model used in this work can measure films

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\* The measured  $C_m$  values are 25% lower than what would be obtained with an unconfined disc [(8)(p.119)].

greater than 10  $\mu$ m thick (0.4 mils) and indicate their surface roughness. Measurements of slime film thickness were made before and after drag testing in most cases.

#### Slime Film Generation

The first attempts to generate tenacious slimes were made using titanium discs as substrata. Titanium was chosen for its well-known corrosion resistance in seawater media. As has been mentioned in a previous report (7), immersion of the discs in a salt-water aquarium containing a population of killfish (*Fundulus* sp.) resulted in slimes which did not remain on the discs during testing. Cultures of microorganisms were then set up which were expected to lead to more stable films on the basis of experience at NRL (Hannan and Patouillet, personal communication). Two strains of aquatic algae were cultured for this purpose using stocks obtained from J. Hannan and C. Patouillet of the Environmental Biology Branch, NRL, and with their assistance and advice. The first was *Chlorella pyrenoidosa*, a unicellular green alga which was grown in Burke's medium (10). The second was *Phaeodactylum tricornutum*, a diatom. (Diatoms are commonly called golden-brown algae). The diatom culture was grown in Guillard-Ryther medium (11). These organisms were maintained in controlled-temperature aquaria with stirring. A gas mixture of 4% carbon dioxide-96% air was continually bubbled into the green algae culture, while the culture medium for the diatom contained sufficient bicarbonate to maintain growth. Medium was routinely renewed weekly.

A third culture was also set up. This was derived from a bacterial slime film which formed upon titanium discs immersed in the Severn River at the Annapolis laboratory of the NSRDC. The bacterial material formed a very tenacious, thick, clear, and tough film when titanium discs were immersed during the spring of 1979 by Mr. N. Smith. However, these were not entirely satisfactory for slime drag testing because silting, and barnacle and algal growth, had also occurred (7). Laboratory culture eliminated these contaminants. The bacteria were grown in artificial seawater (Instant Ocean) of 10<sup>0</sup>/oo salinity, 5gm/liter Difco Peptone, and 1/gm liter Difco yeast extract. This is equivalent to Difco Marine Broth 2216 but for its lower salinity.

Previous attempts to culture slime films on the titanium discs were unsuccessful for two reasons: (1) The films of *Chlorella* (green alga) and the slime bacteria did not resist the scouring action of the fluid during drag testing sufficiently to permit assessment of their effect. The diatom films did enhance drag of the titanium discs but, to our surprise, caused corrosion of the disc to the extent that its roughness, and so its drag when clean, were not similar before and after the experiment. The green alga also caused corrosion.

For these reasons, it was decided to attempt measurements using plastic discs. These were fabricated from 1/8 inch (3.18 mm) commercial sheet poly-(methylmethacrylate) (PMMA) and polystyrene (PS).

The finish as received was used for smooth discs. Attempts were made to roughen several discs with abrasive paper and cloth. Although the goal of roughening the discs was achieved, these discs proved to be toxic to the organisms, and despite rigorous cleaning killed the cultures they were placed in contact with. We have recently managed to restore the compatibility of these roughened discs with algal cultures, but have not yet attempted drag tests with them. Our current thought is that the abrasive material itself, or the cement which attaches it to the paper or cloth backing, or both, become embedded in the plastic discs and are therefore difficult to remove without selective chemical treatments. We are not yet sure which combination of the treatments which we used to restore compatibility with the cultures was the crucial one, and whether the slime films now growing will in fact be sufficiently tenacious for drag testing.

Initial disc sliming attempts were made using cultures contained in 2 gallon or 10 gallon (7 liter or 35 liter) glass aquaria. Algal cultures were illuminated by a pair of 35 watt fluorescent tubes 6 inches from the vessel wall. The cultures were agitated by magnetic stirring bars. In the case of algae, the films generated on the discs were sufficiently tenacious to allow drag testing. Bacterial films, however, were removed by the vigorous flow in the test apparatus. Therefore, an apparatus was assembled as shown in Fig. 2, which permitted bacterial attachment and growth under flow conditions, using an aquarium power filter pump (12). Films grown in this manner were sufficiently adherent to plastic discs in a number of cases to allow drag testing, but were not sufficiently adherent to titanium.

Two titanium discs were exposed to water taken from the Severn River at NSRDC - Annapolis. (Salinity approximately  $10^0/_{\infty}$ ). The discs were suspended vertically in a polyethylene bucket in a building at the seawall. River water was drawn by a self-priming neoprene impeller pump and passed through a ceramic filter (AMF Corp) which nominally retains particulates larger than  $80 \mu\text{m}$ , and then into the bucket containing the discs. The pump was operated for 1 hour at a time twice daily during the 5-day working week at approximately 10 gallons/minute. During this time the bucket overflowed. Between flow periods, the discs remained immersed in the full bucket. The filter served to exclude most of the silt and the macrofouling organisms which had settled on similar discs during previous experiments, and had made assessment of the effect of slime on drag ambiguous.

## RESULTS

1. Only one experiment with the diatom Phaeodactylum on titanium is reported here. It was undertaken in order to determine whether slime growth sufficient to cause significant drag enhancement would occur before appreciable corrosion. We did not in fact achieve a stable film before corrosion was apparent, but the experimental results are presented here to illustrate the effect. The titanium

disc T-17 was immersed horizontally in the diatom culture for 12 days, to allow film formation. It was drag-tested at the Annapolis laboratory in artificial seawater. Film thicknesses on the top surface before and after testing were 5 mil and 2 mil respectively, and zero on the shadowed lower surface. As shown in Fig. 3 drag enhancement decreased during testing from 16% to 5% as the film was modified by the drag testing with a considerable amount of material sloughing off. The film remaining upon the disc after testing was photographed using a stereomicroscope. The stereo pair is shown as Fig. 4. It may be observed in this figure that a rather low degree of coverage of the rough disc with clumps of algal slime was responsible for the final drag increment. Unfortunately, the exposure to algal culture required to grow this film resulted in clearly visible corrosion damage to the titanium disc. (This was reflected in a change in smoothness as measured with the Perthometer (a stylus instrument); average amplitude surface roughness ( $R_A$ ) changed from 11 to 9  $\mu\text{m}$  (18%)). This prevents an unambiguous comparison of drag of the disc after cleaning with previously measured values. For this reason, further studies of titanium discs in diatom cultures were discontinued.

2. The green unicellular alga (Chlorella pyrenoidosa) cultures also caused corrosion of titanium during long term immersion, and films of this alga were not sufficiently tenacious upon titanium for meaningful drag measurements. For these reasons drag testing of films of Chlorella were performed on plastic discs, both polystyrene (PS) and poly(methylmethacrylate) (PMM). The results of drag testing of Chlorella films are shown graphically in Figs. 5 and 6. The drag increments are observed to be  $>10\%$  for films of thickness 40  $\mu\text{m}$  (PS) or 20  $\mu\text{m}$  (PMM).

3. The bacterial culture derived from the Annapolis laboratory sample was grown first in large glass or plastic (polystyrene) dishes, in which discs were immersed. The cultures were agitated by magnetic stirring bars. The slime films grown in this manner were not sufficiently tenacious for successful drag testing. In order to assure tenacious films, the culture apparatus shown in Fig. 2 was used. Because culture medium flowed rapidly over the discs, only tenacious films were permitted to grow. Making use of the flow system, films were grown on titanium and plastic discs.

3a. The result of a drag test upon a smooth titanium disc is shown graphically in Fig. 7. In this figure, it can be seen that there is a considerable drag increment at low speed (low rotational Reynolds number) but that the drag increment vanishes as the speed increases. After maximum speed was reached, and the speed then decreased, there was no significant increment in drag even at those speeds where an increment had previously been observed. Film thickness initially was  $55 \pm 20 \mu\text{m}$ , and this disc was hydrodynamically smooth ( $R_A = 0.05 \pm .01 \mu\text{m}$ ). These data are consistent with a bacterial slime film causing a drag increment of 12% at low speed, but being sloughed off at higher rotational speed.

3b. Polystyrene (PS) and poly(methylmethacrylate) (PMM) discs were also exposed to the bacterial culture under flow conditions. In these cases, exposure for four to six days caused a film to form which caused 10% drag enhancement on PS (Fig. 8), but only 3% drag enhancement on PMM. Film thicknesses were 20  $\mu\text{m}$  before testing in each case, but, although the PS disc retained this film thickness, film thickness on the PMM disc decreased to the detection limit of 5  $\mu\text{m}$  at the edge while retaining its original value near the center. A longer growth period, however, (14 days) resulted in >20% drag enhancement for PMM. In this case, film thickness was 90  $\mu\text{m}$  before, and 50  $\mu\text{m}$  after testing. (Fig. 9). In all these cases, a bacterial film could be detected on the surface by visual inspection before and after testing, and slime films were detectable to the touch through polyvinyl chloride medical examining gloves before cleaning. In one case, a slime film on PMM was completely sloughed off during testing, and yielded zero drag enhancement at high speed, although significant drag enhancement was observed at low speed (Fig. 10).

4. Further studies with roughened plastic discs using the three organisms were not completed because the unexpected toxicity of roughened discs delayed further efforts. Preliminary growth experiments have now made it probable that cleaning with hypochlorite solutions will remedy the toxicity problem, and allow further work.

5. Drag increments of greater than 15% were observed using titanium discs, treated with filtered Severn water, as illustrated in Figs. 11 and 12. Roughness of disc T-12 was 0.4  $\mu\text{m}$ , while that of T-16 was 11  $\mu\text{m}$ , measured with a stylus instrument on clean and dry surfaces.

## DISCUSSION

The experimental study described in this report was undertaken to assess the possible effects of microbial slime upon hydrodynamic drag under hydraulic conditions which reflect realistic ranges of vessel operation. The results to date indicate that certain microbial slime films are sufficiently tenacious to maintain themselves upon surfaces at quite high Reynolds number, and enhance hydrodynamic drag by more than 10%.

These results are consistent with earlier findings that microbial slimes enhance frictional resistance to flow, and extend the observations to hydrodynamic regimes of interest in fast ship operations. Since frictional increments of the order of 10% are significant in ship operation, microbial slime films must be considered a significant potential problem.

The measurements on a rough titanium disc in filtered Severn Estuary water show more than 15% increment in drag over that found with a clean rough disc. The diatom film on a roughened titanium

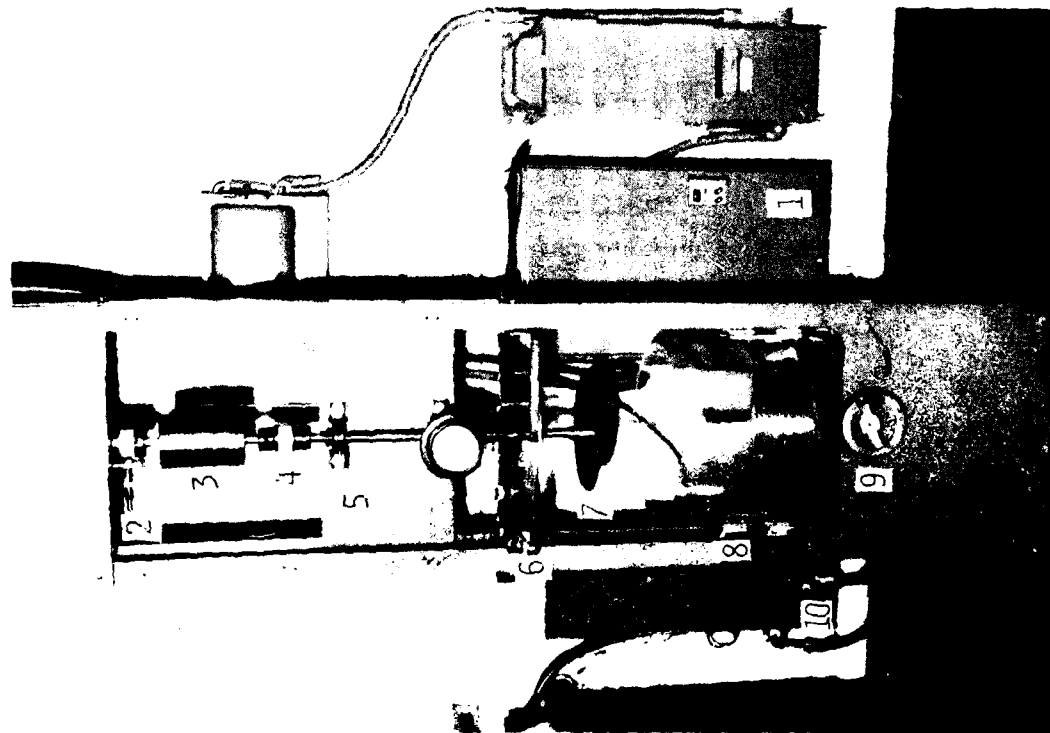
disc was mostly sloughed off during testing, leaving approximately 10% of the surface covered by the slime film. The initial drag increment was 16% at low speed, decreasing to 5%. Thus, even when rough discs are used, there is no evidence as yet to indicate that slimes can decrease drag, although intuitively it seems reasonable that a rough surface might be made effectively smoother by a layer of slime. However, the data are still sparse, and much more work is required before a definitive statement concerning this possibility can be made. Among other factors, the inherent smoothness and viscoelasticity of slime films vary between limits which are not yet explored.

A further point arising from this study is the difference caused by variation of the material forming the friction disc. Growth on the titanium discs was not as tenacious as on the plastics, and the two plastics used, polystyrene and poly(methylmethacrylate) seem to have caused differences in the properties of their microbial slime films during early stages of growth. If further work can elucidate the physical and chemical basis for such differences, important enhancement of antifouling technology might result.

The two types of surface presented to attaching microbes, plastic and metal, represent approximations to the two types of important surfaces on vessels: paint on the hull, which is an organic coating, and propeller blades. Both surface types have been shown to be susceptible to microbial fouling which remains attached to a significant degree according to the criterion of drag, at least for short periods.

The viscoelastic properties of slime films, their relative tenacity on surfaces of different types, and alternative methods of control of these properties, are all obscure at present. They represent areas for further research which have potential for significant improvements in operational capabilities and economy.

It was observed that algal films enhance corrosion of titanium.



- (1) Case for motor power supply and control components
  - (2) Rotational speed sensor
  - (3) Torquemeter
  - (4) Flexible coupling
  - (5) Shaft bearings
  - (6) Top plate, with reservoir for excess liquid surrounding shaft entry hole, liquid pressure gauge, and thermocouple
  - (7) Disc attached to shaft
  - (8) Cylinder container for test fluid, shown in lowered position
  - (9) Crank for cylindrical container elevator
  - (10) Container filling and drain lines
- Motor is located behind panel at top of frame. Electronic readout components for speed, temperature and torque not shown.

Fig. 1 — Friction disc tester

## CULTURE APPARATUS FOR MICROBIAL FILMS

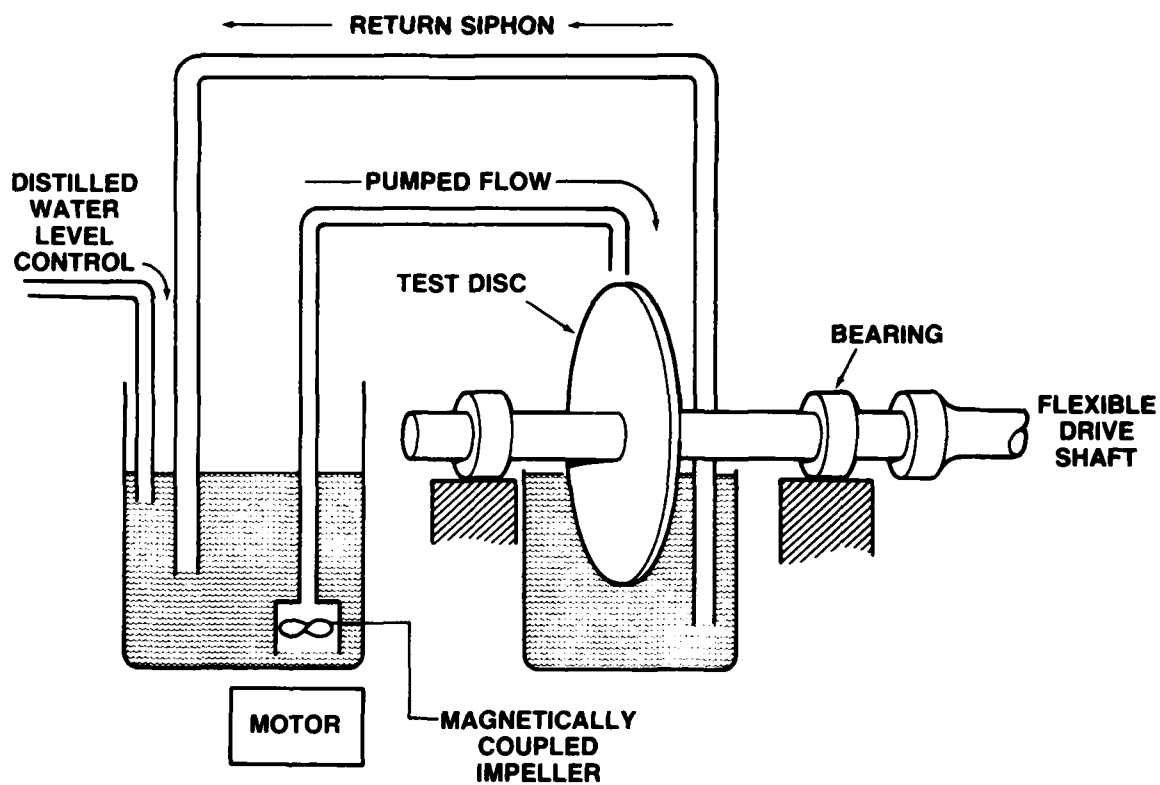


Fig. 2 — Culture apparatus for microbial films

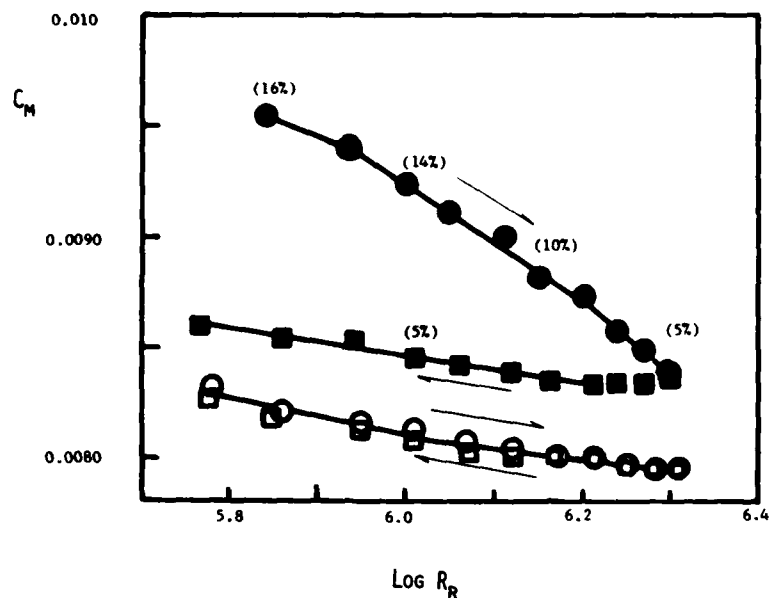


Fig. 3 — Drag test of diatom slime on titanium disc

- Slimed disc, increasing speed
- Slimed disc, decreasing speed
- Cleaned disc, increasing speed
- Cleaned disc, decreasing speed

Numbers in parentheses indicate percent drag enhancement.  
Arrows indicate sequence of data collection.

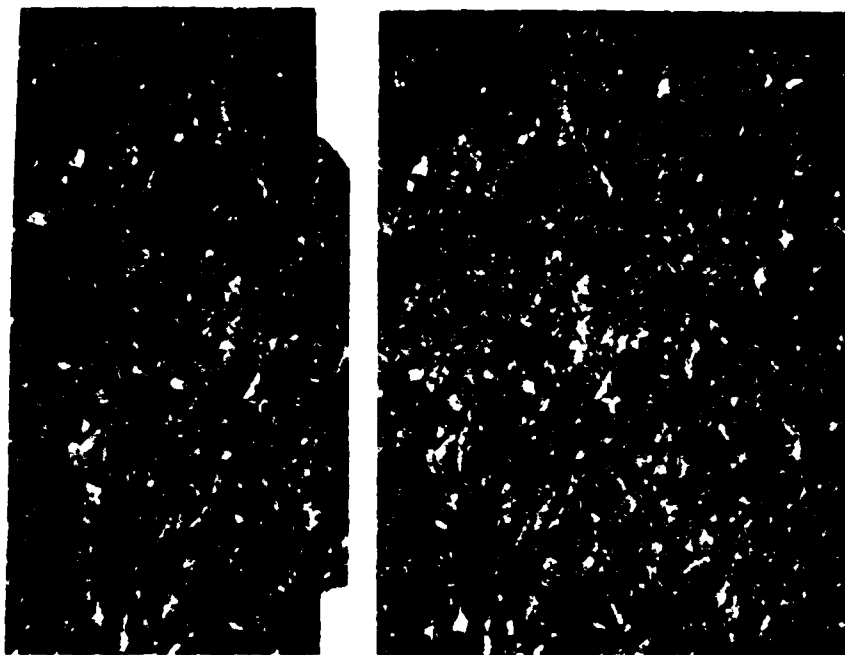


Fig. 4 — Residual slime on disc after test shown in Fig. 3, before cleaning.  
(Stereophoto pair). Field width corresponds to 4 mm.

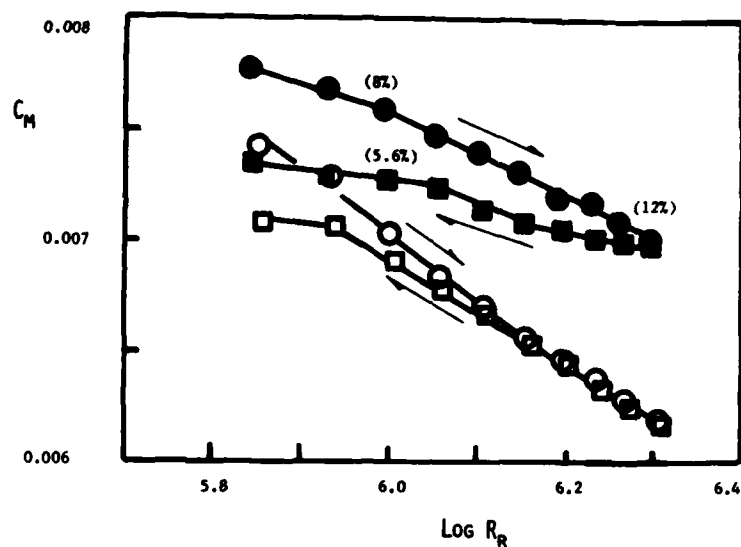


Fig. 5 — Drag test of *Chlorella* slime on (PS) disc. Symbol meanings as in Fig. 3.

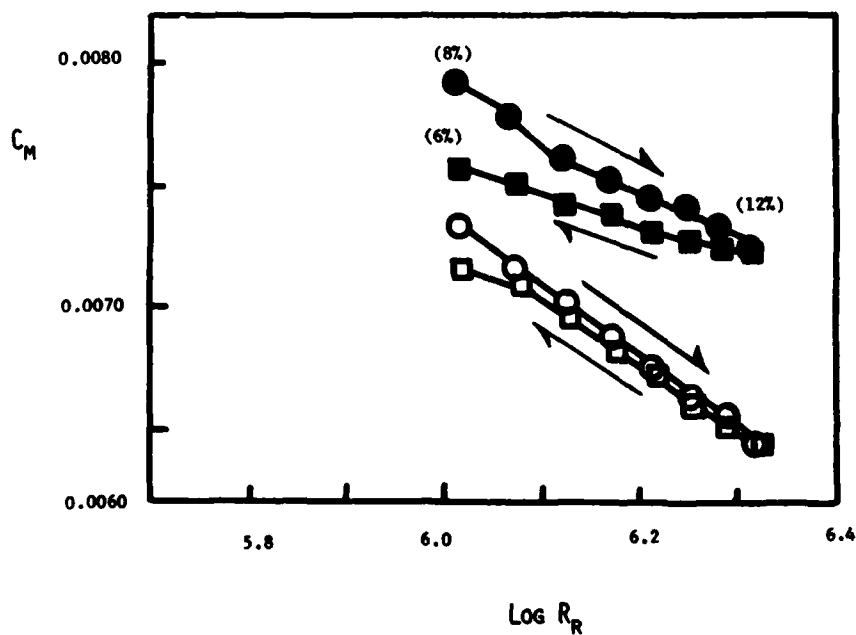


Fig. 6 — Drag test of *Chlorella* slime on (PMM) disc. Symbol meanings as in Fig. 3.

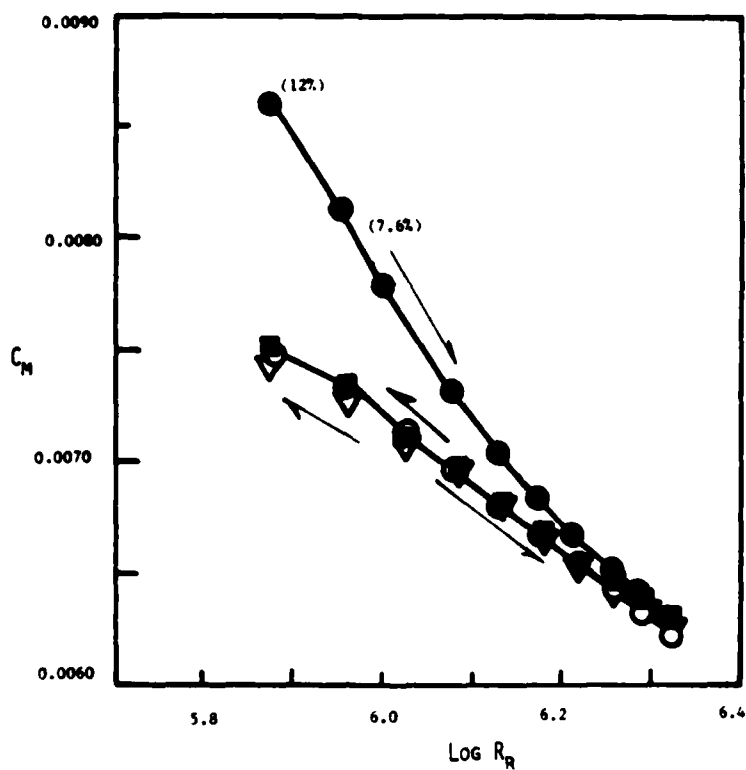


Fig. 7 — Drag test of bacterial slime on titanium disc

- Slimed disc, increasing speed
- Slimed disc, decreasing speed
- Cleaned disc, increasing speed
- ▽ Cleaned disc, decreasing speed

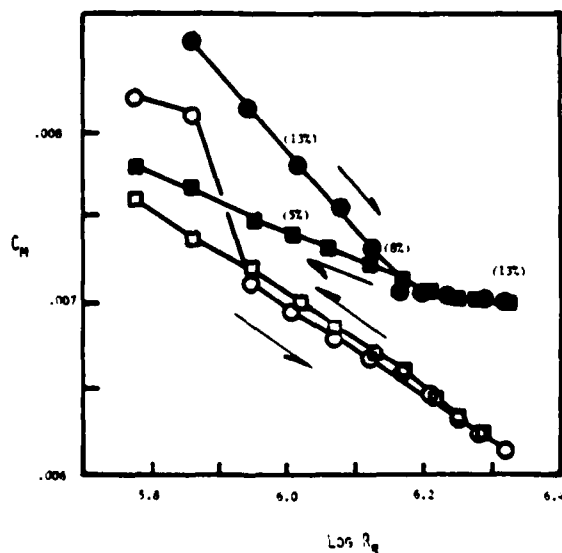


Fig. 8 — Drag test of bacterial slime on (PS) disc. Symbol meanings as in Fig. 3.

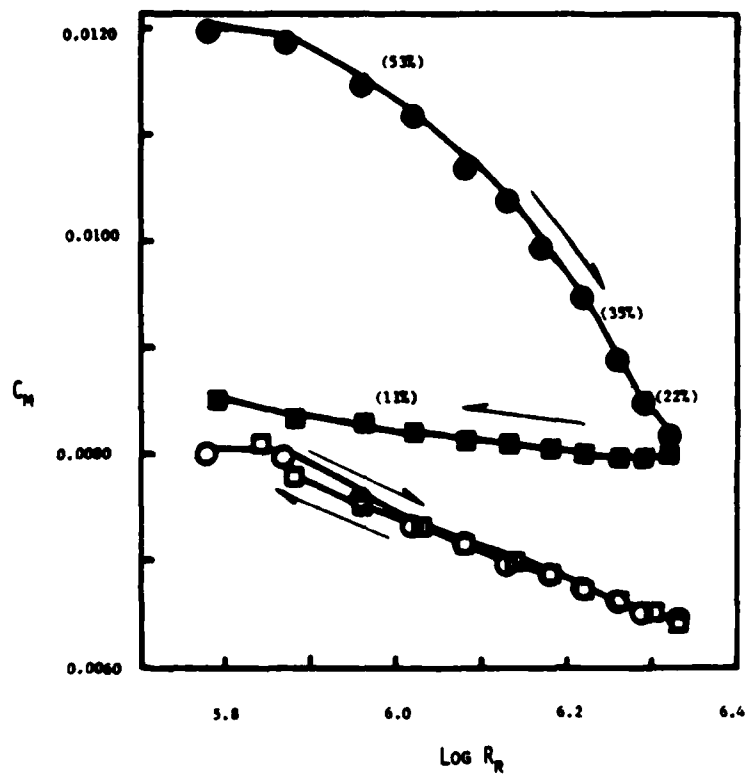


Fig. 9 — Drag test of bacterial slime on PMM disc.  
Symbol meanings as in Fig. 3.

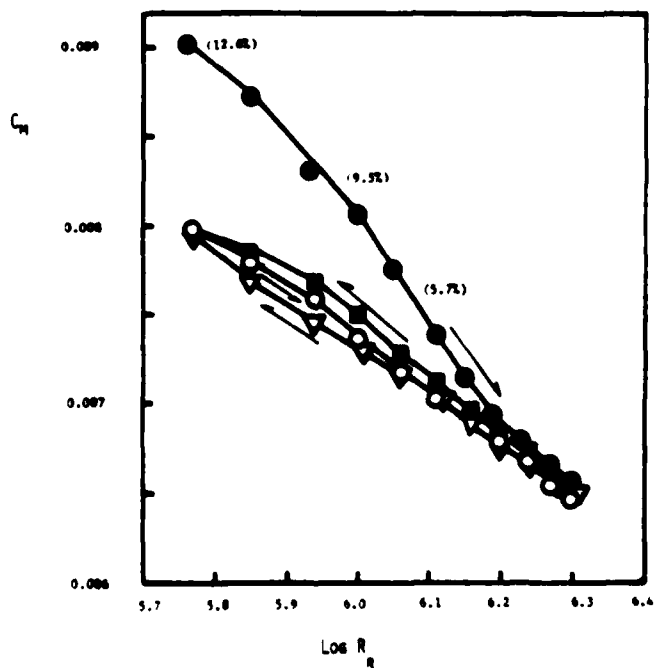


Fig. 10 — Drag test of bacterial slime on PMM disc.  
Symbol meanings as in Fig. 7.

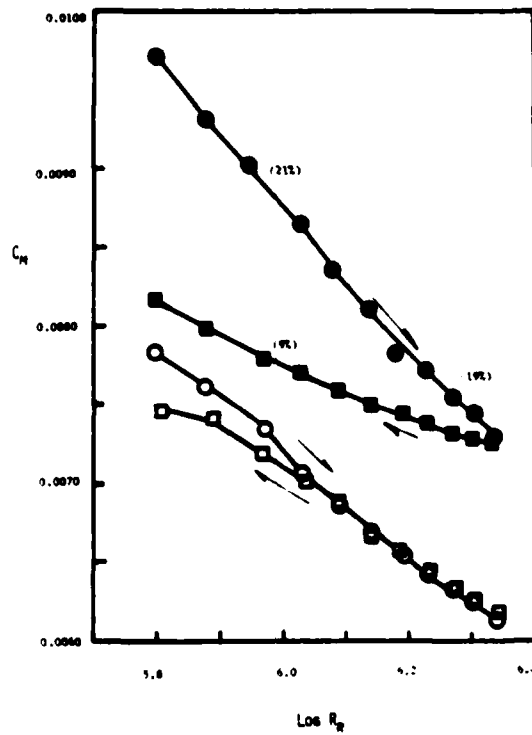


Fig. 11 — Drag test of slime from Severn River water on titanium disc T-12 (smooth). Symbol meanings as in Fig. 3.

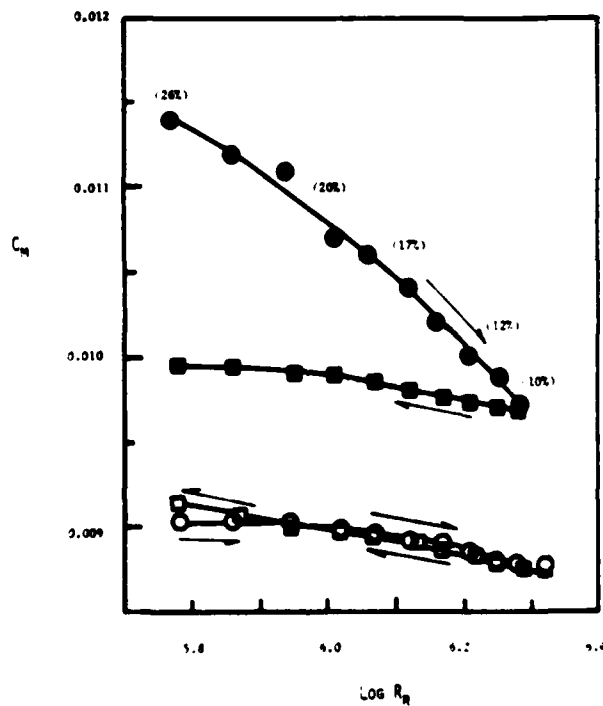


Fig. 12 — Drag test of slime from Severn River water on titanium disc T-16 (rough). Symbol meanings as in Fig. 3.

## ACKNOWLEDGMENT

The testing apparatus described in this report was operated by Mr. Don Lester, Mr. Neil Smith or Mr. Tom Gracik of DTNSRDC - Annapolis who also computed the moment coefficients from the raw data. The author also wishes to thank them for many fruitful discussions during the course of the work.

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